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Magnetotransport properties of untwinned $YBa_2Cu_3O_y$ single crystals: Novel 60-K-phase anomalies in the charge transport

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We present the result of our accurate measurements of the a- and b-axis resistivity (ρ_a and ρ_b), magnetoconductivity $\Delta\sigma/\sigma$, Hall coefficient R_H, and the a-axis thermopower S_a in untwinned $YBa_2Cu_3O_y$ single crystals in a wide range of doping ($6.45 \leq y \leq 7.0$). The systematics of our data reveals a number of novel 60-K-phase anomalies in the charge transport: (i) Temperature dependences of ρ_a show anomalous overlap below ∼130 K for $6.65 \leq y \leq 6.80$, (ii) Hall mobility μ_H shows an enhancement near $y \simeq 6.65$, which is reflected in an anomalous y dependence of σ_{xy}, (iii) With decreasing temperature R_H shows a marked drop upon approaching T_c only in samples with $6.70 \leq y \leq 6.85$, (iv) Superconducting fluctuation magnetoconductivity is anomalously enhanced near $y \simeq 6.7$, and (v) H_{c2} is anomalously reduced near $y \simeq 6.70$. We discuss that the fluctuating charge stripes might be responsible for these anomalies in the charge transport.

Keywords: Transport Properties, 60-K phase, Superconducting Fluctuations, Coherence Length

I. INTRODUCTION

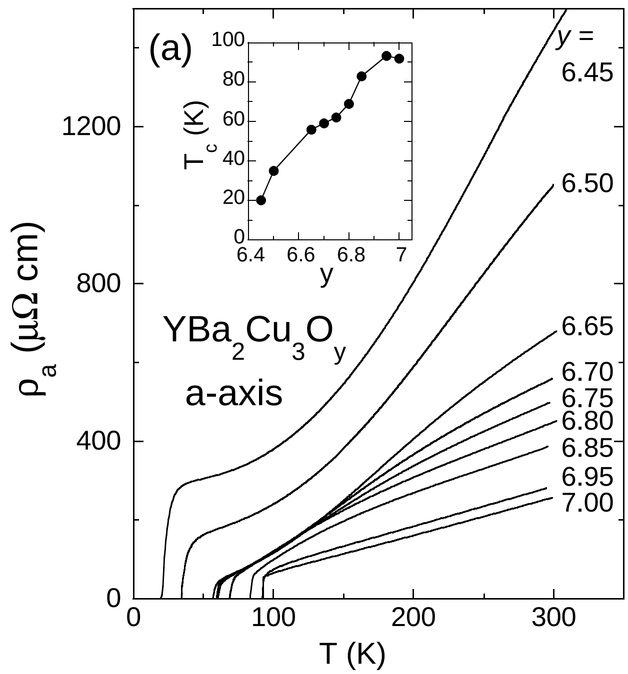
In $YBa_2Cu_3O_y$ (YBCO) compound, an increase in the oxygen content y from 6 to 7 causes the hole doping into the CuO_2 planes (above $y \simeq 6.2$) and leads to superconductivity (above $y \simeq 6.4$). The dependence of T_c on y is non-trivial and there is a well-known plateau with $T_c \simeq 60$ K for y of around 6.7 ("60-K plateau" or "60-K phase"). Both an oxygen-ordering scenario [1] and an 1/8-anomaly scenario [2] have been discussed for the origin of the 60-K plateau, but the case remains controversial. To understand the true nature of the 60-K phase in YBCO, we have conducted systematic measurements of the transport properties across the 60-K phase, which reveal clear electronic anomalies in the 60-K phase and thus indicate an electronic origin of the 60-K plateau. In this paper, we summarize the novel 60-K-phase anomalies we found in the charge transport in YBCO and discuss their possible origin in conjunction with the self-organization of the holes into stripes.

II. EXPERIMENTAL

It should be noted that the oxygen arrangement in the Cu-O chain layers is essentially random, causing complications to the study of YBCO; for example, for a given y the actual hole doping can differ depending on the arrangement of the O atoms, and the O atoms in the Cu-O chains can rather easily rearrange at room temperature, which causes the "room-temperature (RT) annealing effect" [3]. For this work, the crystals are always quenched at the end of the high-temperature annealing (which tunes the oxygen content) and detwinning is performed at temperatures below 220°C after the annealing. The samples are left at room temperature for at least a week for the oxygen arrangement to equilibrate before the measurements; therefore, the oxygen atoms on the chain sites are expected to be locally ordered (because of the RT annealing) but macroscopically uniform (because of the quenching) [3]. (Note that a long-time annealing at relatively low temperature (∼100°C) causes a macroscopic phase separation in heavily-underdoped samples [4] and messes up the transport properties.) Our procedure ensures very good reproducibility of the transport properties, as has been demonstrated in Ref. [5]. In particular, we have determined the absolute values of the resistivity and the Hall coefficient for a given y with the accuracy of 5%; this gives us confidence in discussing the systematics of the transport properties across the 60-K phase. Details of the measurement techniques are described in Refs. [5–7].

III. RESULTS AND DISCUSSIONS

Let us start with the resistivity behavior. Figure 1(a) shows the temperature dependences of ρ_a for a wide range of oxygen contents, $y = 6.45 - 7.0$. Remember that the Cu-O chains run along the b-axis and thus ρ_a is not complicated with the conductivity of the chains [8]. We emphasize that at least 3 samples are measured for each y and the data are reproducible within 5%; in fact, Fig. 1(a) is a summary of the measurements of more than 30 samples. One can immediately notice in Fig. 1(a) that the $\rho_a(T)$ data for $y = 6.65 - 6.80$ show clear overlap below ∼130 K. Note that in the underdoped YBCO the pseudogap opening can be inferred from a downward deviation from the high-temperature T-linear dependence [9], and thus the overlapping of $\rho_a(T)$ is observed in the pseudogap state. Figure 1(b) shows the corresponding evolution of $\rho_b(T)$ with y; ρ_b is generally smaller than ρ_a for the same y, which is believed to be due to the finite



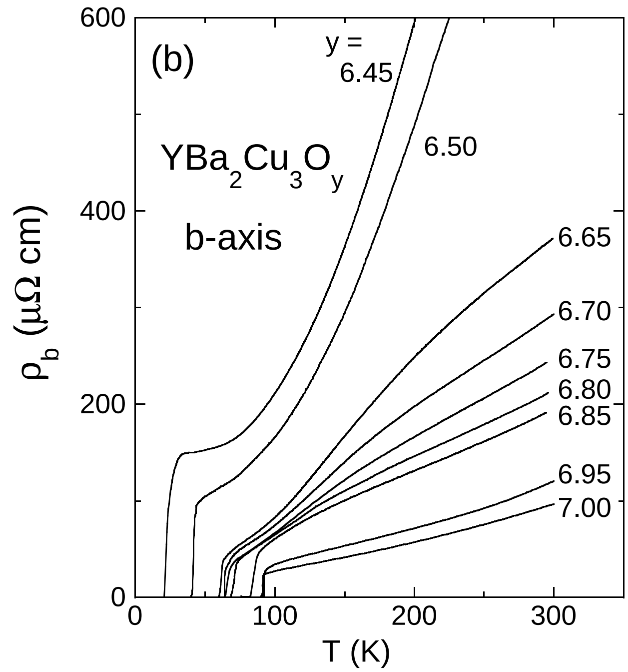


FIG. 1. T dependences of (a) ρ_a and (b) ρ_b for untwinned YBCO crystals in 0 T. Inset in (a): Phase diagram of zero-resistance T_c vs. y.

chain conductivity [8]. The $\rho_b(T)$ data do not show as clear overlap in the 60-K phase as the $\rho_a(T)$ data.

The overlap of the $\rho_a(T)$ data is very unusual. Unless the effective mass m^* of the charge carrier in YBCO is anomalously changing with y (which is very unlikely), the y-independence of ρ_a can have only two possible origins: (i) both the carrier concentration n and the scattering time τ remain unchanged with y, or (ii) a change in n is compensated by a change in τ. To clarify which

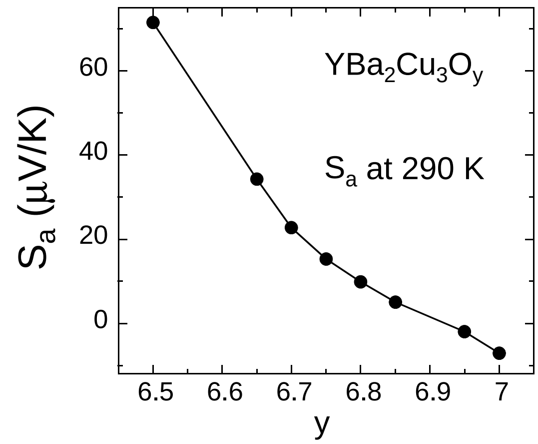


FIG. 2. y dependence of the a-axis thermopower at 290 K.

of the two is actually the case, we measured the room-temperature thermopower $S(290\text{K})$, which is generally believed to reflect the change in the hole concentration and thus may be used as a guide to estimate n [2]. Figure 2 shows the y dependence of the thermopower measured along the a-axis at 290 K, $S_a(290\text{K})$, which is expected to be free from the contribution of the Cu-O chain transport. The $S_a(290\text{K})$ data show a continuous change across the 60-K phase, which strongly suggests that n is continuously changing with y in our samples. Therefore, among the two possibilities listed above, it is more likely that a change in n is somehow compensated by a change in τ in the 60-K phase.

Examination of the Hall channel in the in-plane transport gives us a clue to the (phenomenological) origin of the anomaly in $\rho_a(T)$. In YBCO, it is expected that σ_{xy} is governed by the properties of the planes (since the Cu-O chains contribute little to σ_{xy} because of their one-dimensionality), while the Hall resistivity ρ_{xy} [which is expressed as $\rho_{xy} \simeq \sigma_{xy}/(\sigma_{xx}\sigma_{yy})$ with $\sigma_{xx} \simeq 1/\rho_a$ and $\sigma_{yy} \simeq 1/\rho_b$] is affected by the properties of the chains through σ_{yy}. Therefore, σ_{xy} is a better indicator of the properties of the planes compared to R_H. Perhaps reflecting this situation, σ_{xy} at 125 K shows a clearly anomalous y dependence while such anomalies are smeared out in the y dependence of R_H [Figs. 3(a) and 3(b)]. The nature of this anomaly in the Hall channel is best understood by the plot of the Hall mobility in the planes, $\mu_H = \sigma_{xy}/(B\sigma_{xx})$ (Fig. 4), which reflects τ/m^* and does not include n in the Drude picture. One can clearly see that μ_H is anomalously enhanced near y=6.65, particularly at 125 K [where the overlap of $\rho_a(T)$ is observed]. Therefore, it appears that the scattering time τ gets enhanced upon reducing y from 6.80 to 6.65 and this change in τ cancels the change in n, causing the y-independent resistivity in the CuO_2 planes for $y = 6.65 - 6.80$. It should be noted that this anomalous enhancement of τ takes place only when the pseudogap opens, and thus the overlap of $\rho_a(T)$ is observed only

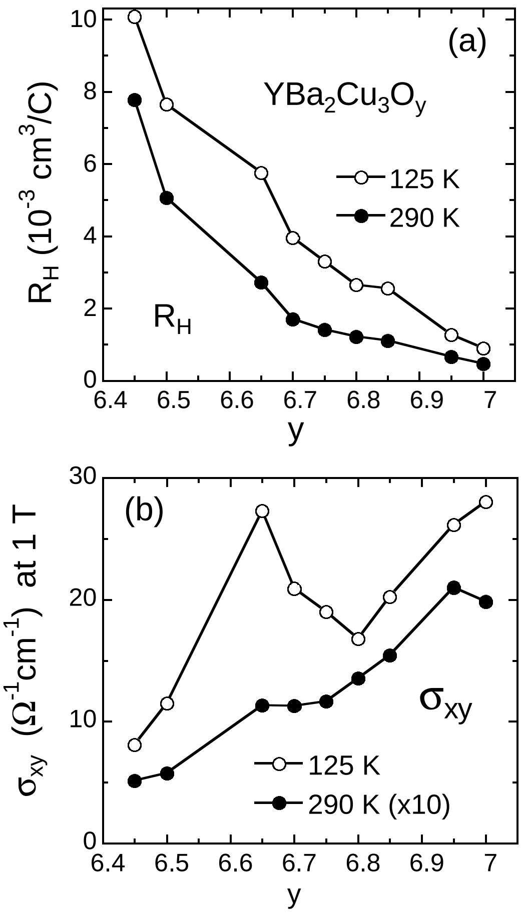


FIG. 3. y dependences of (a) raw R_H and (b) Hall conductivity σ_{xy} (calculated for B=1 T) at 125 and 290 K.

below ~130 K.

The Hall effect reveals yet another aspect of the anomalies in the 60-K phase. Figure 5(a) shows the temperature dependences of R_H (measured with the current along the a-axis) for a wide range of y; the data points in Fig. 3(a) are extracted from this series of data. One may

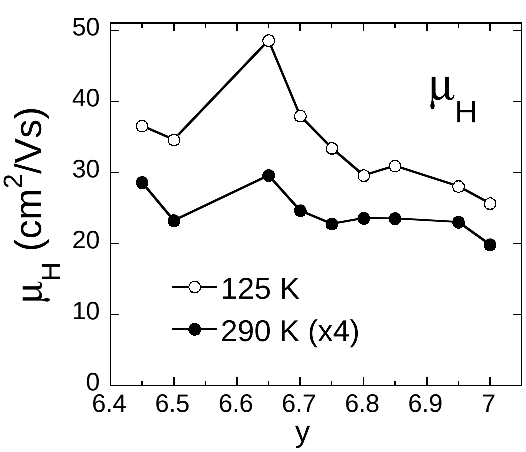


FIG. 4. y dependence of the Hall mobility at 125 and 290 K.

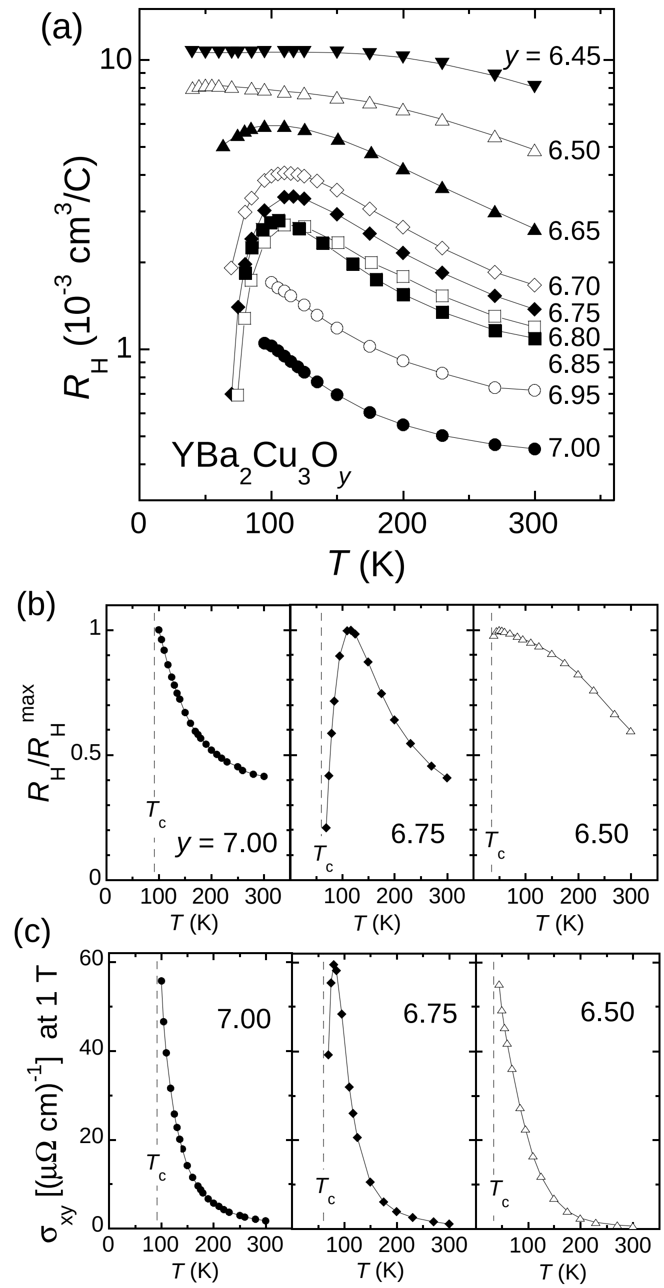


FIG. 5. (a) T dependences of R_H for various y. (b), (c): T dependences of R_H and σ_{xy} (calculated for B=1 T) for samples with y = 7.00, 6.75, and 6.50; the R_H data are normalized by the maximum values for each y in (b).

notice in Fig. 5(a) that only the data for $y = 6.65 - 6.85$ show noticeable drop in $R_H(T)$ with lowering temperature upon approaching T_c; this situation becomes obvious in Fig. 5(b), where the $R_H(T)$ data for y = 7.0, 6.75, and 6.50 are compared, with clearly indicated T_c. It is apparent that only the 60-K-phase sample shows a marked drop in $R_H(T)$ from well above T_c and the data seem to be heading towards zero. To demonstrate that this anomaly is not extrinsically caused by the effect of the Cu-O chains on R_H, we show similar comparison of

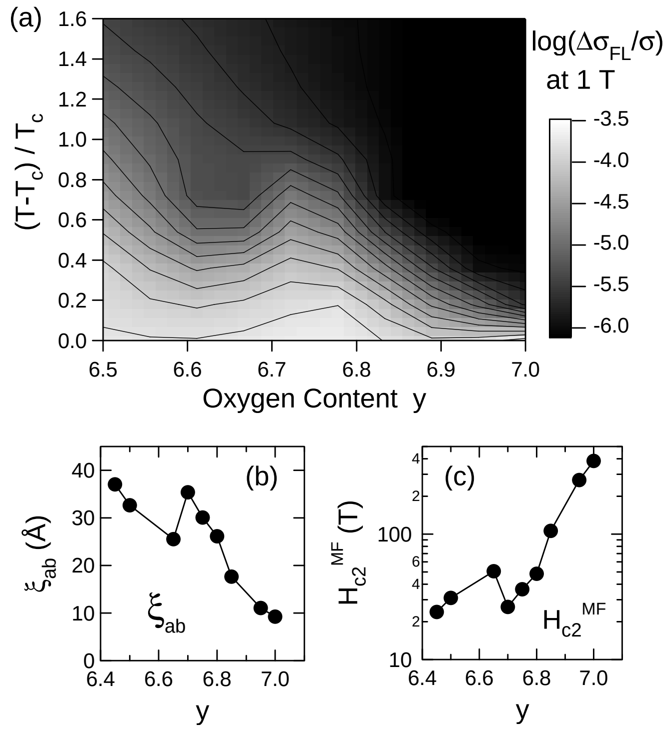


FIG. 6. (a) Evolution of the fluctuation MC in the $(T - T_c)/T_c$ vs. y plane. (b) y dependence of ξ_{ab} obtained from the ALO fits. (c) y dependence of the mean-field upper critical field calculated from ξ_{ab}.

$\sigma_{xy}(T)$ for the three compositions [Fig. 5(c)], which again shows that the anomalous T dependence is observable (though a bit weakened) only in the 60-K phase sample. This remarkable drop in R_H is somewhat reminiscent of the $R_H(T)$ behavior in Nd-doped $La_{2-x}Sr_xCuO_4$ [10], where it has been discussed that some peculiarity of the charge transport [10–12] imposed by the stripes [13] is responsible for the drop in R_H. Thus, the anomaly observed in the $R_H(T)$ behavior is suggestive of a role of the stripes in the 60-K phase of YBCO.

We also measured the magnetoresistance in ρ_a in both the transverse and the longitudinal geometries, from which we extract orbital magnetoconductivity (MC). The orbital MC at high temperatures, whose temperature dependence is very well fitted with $[bT^2 + c]^{-2}$ [14,15], is due to the normal-state contribution; the data show additional contribution at lower temperatures, which can be identified as the Aslamazov-Larkin orbital (ALO) component of the superconducting fluctuation MC [14]. The full details of the data and their analysis will be published elsewhere [15], and here we show only the fluctuation MC ($\Delta\sigma_{\rm FL}/\sigma$) obtained after the analysis. Figure 6(a) shows how the fluctuation MC evolves in the $(T - T_c)/T_c$ vs. y plane. One can see that there is a general growth of $\Delta\sigma_{\rm FL}/\sigma$ with decreasing y, but on top of this trend there is a marked enhancement of $\Delta\sigma_{\rm FL}/\sigma$ near $y \simeq 6.7$. An enhancement of $\Delta\sigma_{\rm FL}/\sigma$ means that the characteristic magnetic-field scale to suppress the superconducting fluctuations is smaller, which suggests that H_{c2} is reduced in the 60-K phase. In fact, when we extract the in-plane coherence length ξ_{ab} by fitting the $\Delta\sigma_{\rm FL}/\sigma$ data to the ALO formula, obtained ξ_{ab} [Fig. 6(b)] shows an anomalous enhancement in its y dependence near $y \simeq 6.7$; this gives rise to a reduction of the mean-field upper critical field $H_{c2}^{\rm MF}$ [$\equiv \Phi_0/(2\pi\xi_{ab}^2)$] as shown in Fig. 6(c).

IV. STRIPES?

All the above results indicate that the *electronic* state in the CuO_2 planes near $y \simeq 6.7$ is somewhat anomalous compared to other composition and that the 60-K-phase anomalies are definitely not simply due to oxygen ordering. The origin of the electronic anomaly in the 60-K phase is not clear at this stage, but an intriguing possibility is the charge stripes, because the drop of R_H with decreasing temperature observed in the 60-K-phase samples is most easily associated with the stripe physics [10–12]. Below we propose a highly speculative scenario, which just describes one possibility: Suppose that the physics in the whole phase diagram is governed by the fluctuating stripes or "electronic liquid crystals" (as is proposed by Kivelson *et al.* [16]) and that the superconductivity is caused by the fluctuating stripes. If there is a quantum critical point (QCP) associated with the stripes near $y \simeq 6.7$ [17], the superconductivity may be weakened at such QCP (which leads to a reduction in H_{c2} and a plateau in T_c). Since the fluctuations are always enhanced near QCP, the charge mobility may also be enhanced. Thus, though highly speculative, it is possible to qualitatively understand the observed anomalies in the 60-K phase in terms of the electronic liquid crystal picture. In the above scenario, the drop in $R_H(T)$ should be due to the particle-hole symmetry [11,12] rather than the suppression of the transverse motion of charges [10].

V. SUMMARY

We have systematically measured the transport properties of untwinned YBCO single crystals in a wide range of doping and found that the behaviors of $\rho_a(T)$, $\mu_H(y)$, $R_H(T)$, $\Delta\sigma_{\rm FL}(y)$, and $H_{c2}^{\rm MF}(y)$ all show novel anomalies in the 60-K phase. These anomalies are clearly of electronic origin, and possibly related to the stripe physics in this compound.

VI. ACKNOWLEDGMENTS

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